Marco Polo Mission

Executive Summary

Written by	***Responsibility***
Gino Bruno Amata	Study Manager
Verified by	
Stefano Cesare	Head of TAS-I BOOS Business Acquisition and Advanced Projects
Approved by	
N/A	Product Assurance
N/A	Configuration Management
N/A	System Manager
Gino Bruno Amata	Program Manager Gino Bruno Amata
Documentation Manager	
Rosetta Cavaglià	RCav 30/11/2009

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1. INTRODUCTION

Marco Polo is one of the six candidate medium-class (M) scientific missions of the ESA Cosmic Vision (CV) program. If selected, it will undergo a Definition Phase and then an Implementation Phase for launch in 2018.

One of the Marco Polo assessment studies was led by Thales Alenia Space Italia (responsible of the System Definition, the Earth Re-entry Capsule and the Spacecraft Design) with Thales Alenia Space France (responsible of Guidance Navigation & Control and of Touch & Go System) and Selex Galileo (responsible of Sampling Acquisition & Transfer System).

The scope of this study was to provide technical definition and programmatic assessments of the whole space segment (Spacecraft + Earth Re-entry Capsule + Guidance Navigation & Control and of Touch & Go System + Sampling Acquisition & Transfer System), including development schedule and industrial costs evaluation. This information will support the selection process of the M mission to enter the definition Phase in the first half of 2010.

2. MISSION OBJECTIVES AND OVERVIEW

2.1 Mission Objectives

The basic objective of Marco Polo is to safely return to Earth a sample of a primitive Near Earth Object (NEO). The mission shall place the samples in their local and global context and therefore enable characterisation of the selected NEO at different scales allowing the selection of the most appropriate sampling site(s). As additional goal, the mission should provide complementary science results not achievable from the samples themselves.

2.2 Mission Overview

The mission is based on a single Spacecraft (S/C) to be launched directly into its interplanetary cruise by Soyuz-Fregat. At the Asteroid, an observation campaign will start allowing gathering information useful both for scientific purposes and for navigation and control. Using this information, three candidate sampling sites of scientific interest and suitable for sampling will be selected for detailed characterization.

During the last phase of operations the S/C will be commanded to approach the surface on one of the sampling sites and will perform an autonomous optical guided touch and go manoeuvre. Thanks to the sampling mechanism included in each one of the three legs, exploiting the residual kinematics energy at touch down, up to three different samples can be collected on each sampling site. On completion of the sampling operation the legs will fold allowing the transfer of the samples inside the S/C and into the Earth Re-entry Capsule (ERC).

Additional time will be available for extended characterisation of the asteroid before the injection into the re-entry transfer trajectory that will bring the S/C back to Earth. In proximity of the Earth the ERC will be released entering the atmosphere to deliver the samples safely on Earth surface.

Space System	Spacecraft Earth Re-entry Capsule	
Launch	Soyouz Fregat 2.1b Dedicated Adapter Direct escape strategy with 2 Earth fly-by's	
Spacecraft		***Baseline***
	Design lifetime [y]	7
	Attitude control	three-axis stabilized
	Total mass at launch [kg]	1558
	Spacecraft main body dimensions [mm]	3260 mm x 3260 mm x 906 mm
	Solar Array [mm] / [m^2]	5380 x 1400 / 7,55
		GaAs - RWE3G-ID2-150-8040 Triple junction solar cells
	Propulsion	8+8 4N - 2+2 22N bi-propellant
	Power	SAFT 18650F Li-Ion cells
		28 V regulated BUS
	Comms	X-band HGA 1,3 m
		X-band MGA
		X-band 2xLGA
Mission	Hyperbolic escape V [km/s]	3.05
	Transfer duration [y]	3.4
	Min/Max Sun distance [A.U.]	0,8 / 1,55
	Max Earth distance [A.U.]	2.4
	Total DV [m/s]	1648
Operations	*Ground stations:*	
	LEOP	Kourou / Vilspa [15m]
	Deep Space	New Norcia / Cerberos [35 m]
		ESA ESTRACK network / JAXA network
ERC		***Baseline***
	Design lifetime [y]	7
	Total mass [kg]	68.81
	Dimensions [mm]	Ø 800 x 404
	Power	Li-Thyonil cells
	Comms	UHF
		Wraparound antenna
	Descent Landing System	Parachute Ø 800 mm
		Back Shield release
Mission	Inertial velocity at ERC entry point [km/s]	12.1
	Entry	Prograde
	Flight Path Angle [deg]	-10 ± 1

3. PAYLOAD

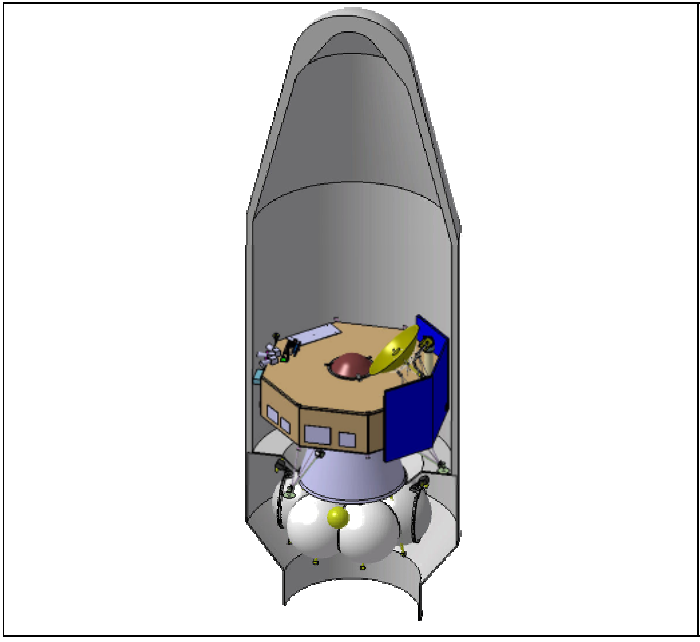
The payload suite consists in remote sensing payload instruments, enabling the global and local characterisation of the asteroid and the sampling sites, and the touchdown instrument operating during sampling.

- *Orbital payload instruments*
    - Wide angle camera (WAC)
    - Narrow angle (high resolution imaging) camera (NAC)
    - Laser altimeter
    - Visible and near infrared spectrometer (VisNIR)
    - Mid infrared spectrometer (MidIR)
    - Radio science experiment (RSE)
    - Neutral particle analyzer (NPA)
- *Touchdown instrument*
    - Close up camera (CUC)

The three cameras (WAC, NAC and CUC) form the Marco Polo Camera System (MPCS). It foresees an integrated approach for the NAC and WAC into a single Command and Data Processing Unit (CDPU). The instrument is complemented by general electronics equipment (for voltage, power and harness) that serves the NAC, WAC and CuC.

4. SPACECRAFT CONFIGURATION

In Figure 2.2-1 and Figure 2.2-2 some views showing the Marco Polo spacecraft configuration beneath the Soyuz ST fairing and in operative condition are shown. The S/C configuration is organized around a central cone, connected to eight lateral panels (equipment panels) by means of eight shears panels. Optical and IR payloads are located externally on anti-sun lateral panel, while the other payloads are placed on bottom platform (see Figure 2.2-2).



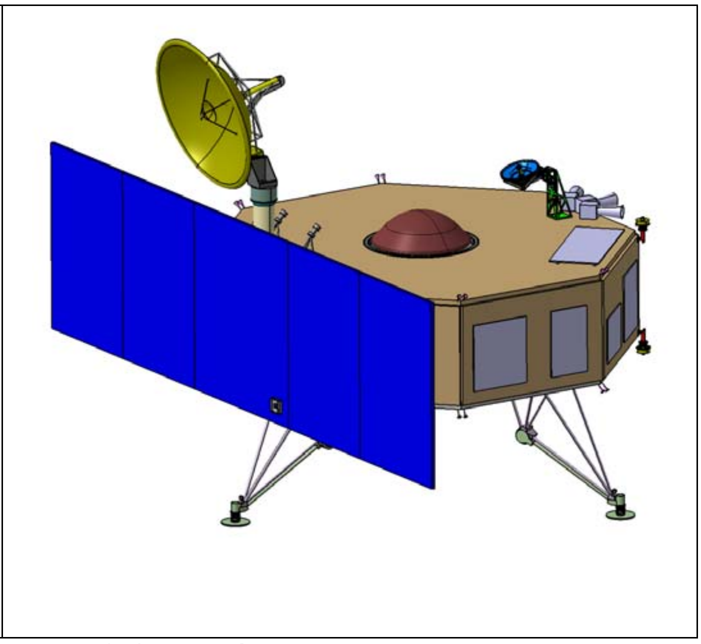


Figure 2.2-1 Marco Polo Spacecraft Stowed/Deployed

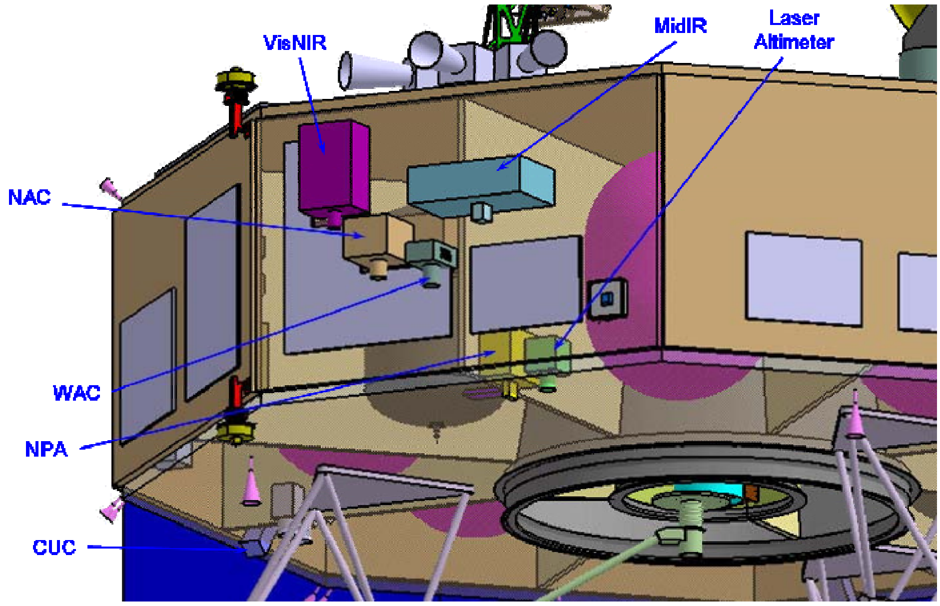


Figure 2.2-2 Payload Accommodation on the Spacecraft

5. TOUCH & GO SAMPLING LEGS

5.1 Touch & Go Legs Overall Design

The Touch & Go (T&G) device is composed with 3 identical legs located symmetrically on the backside of the spacecraft. These legs consist in a tubular, articulated structure with motorized hinge, designed by TAS, which supports in its pad the sampling tools studied by Selex Galileo. The main functions of T&G legs are:

- ✓ To guarantee S/C stability during touchdown phase
- ✓ To transfer the sampler towards the canister system
- ✓ To re-deploy the arm (to allow another sample transfer in case of several sampling performed)

Each leg is composed of a Hold & Release Mechanism (HRM) structure made with 7 carbon tubes linked by aluminium bracket. The resulting mass (per leg) is close to 12 kg.

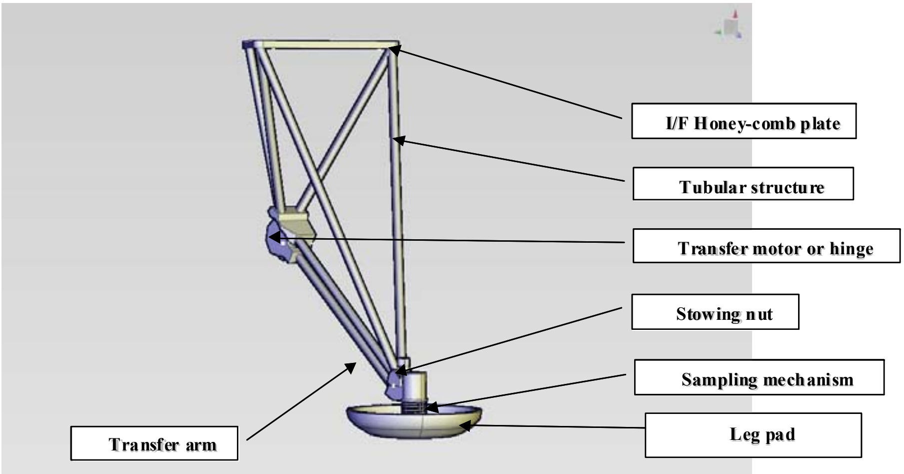


Figure 5.1-1 T&G motorized legs in deployed configuration

5.2 Sapling Collection Operational Sequence

Folowing figure illustrates the sampling collection sequence performed through the proposed T&G approach.

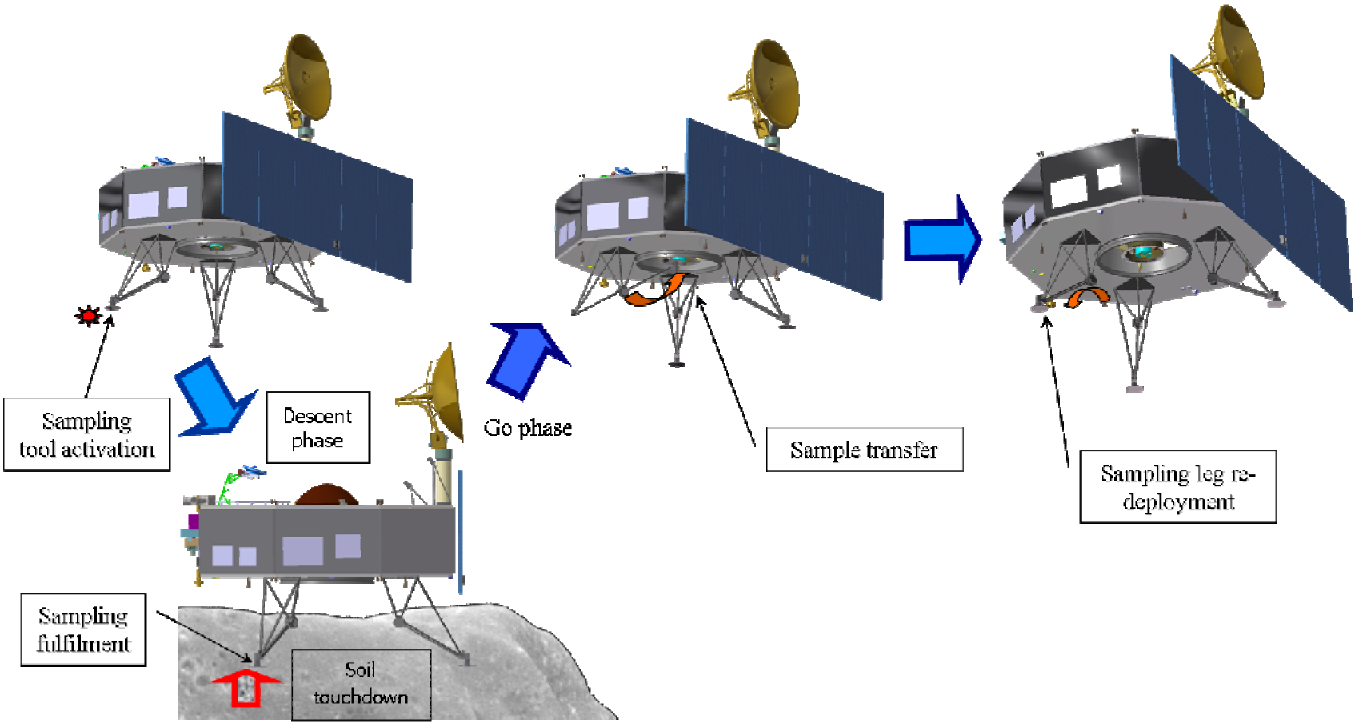


Figure 5.2-1: Operational sequence for the sampling collection

6. SAMPLING ACQUISITION & TRANSFER SYSTEM

The overall system is composed of the following subsystems:

i. a Sampling System based on the push action of the S/C on the soil
ii. a Recovery System based on the articulated landing legs with a double task: to stabilize the S/C during the touch phase and to deliver the sample from the sampling tool to the transfer system
iii. a Transfer System (Sample Canister + Canister Transfer System) based on a rotational joint, a linear joint and a canister to contain the sample
iv. a re-entry capsule placed in the center of the S/C

6.1 Sampling Tool and Transfer and Containment System Description

A Sampling Tool is integrated into the pad of each leg. The tool has a linear degree of freedom and no rotational degrees of freedom. In fact the nature of the soil (very loose) allows collecting the sample just through the pushing action exerted by the S/C during the touchdown phase. The tool has been designed to return the pad\tool in the initial condition for performing the next touchdown.

The Canister Transfer System is dedicated to deliver the sample from the leg to the re-entry capsule. The sample is sealed before return to Earth.

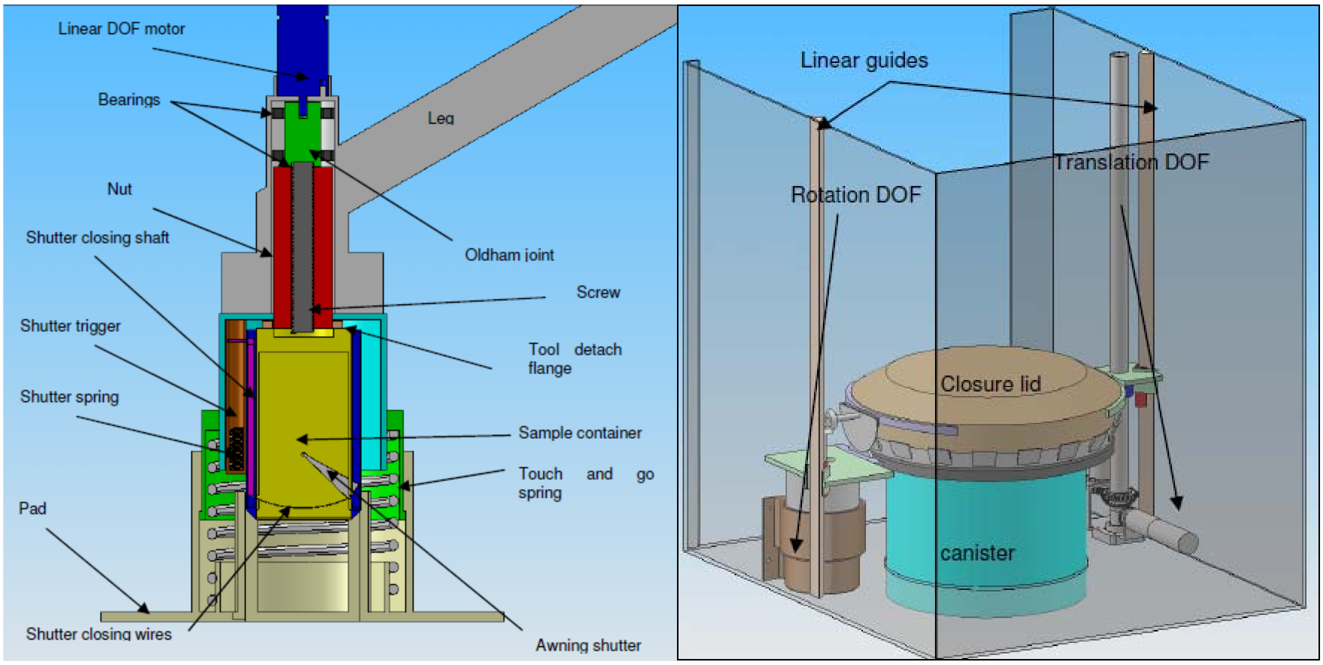


Figure 6.1-1 Overview of the sampling tool (left) and Transfer system with 2 DOFs (right)

In summary a complete Sampling Acquisition and Transfer System consists of: Sampling Tool (3), Canister Transfer System (1) and Sample Canister (1), for a total mass of about 9 kg.

7. GUIDANCE NAVIGATION & CONTROL FOR PROXIMITY OPERATIONS

7.1 Proximity Operations

When the spacecraft has completed the approach phase to the asteroid, the proximity operations are initiated. The operational scenario of the proximity operations is described below:

- Characterisation orbit: after the approach phase the spacecraft is positioned into a close to-circular orbit around the asteroid. The distance will be initially of the order of 5 km, and will be progressively reduced to 2.5 km. The spacecraft will stay on this orbit during a few months in order to image the global shape of the asteroid and build a topographical model of it. The spacecraft is actively controlled in order to maintain its orbit stable. Uncontrolled orbits are also performed for gravity modelling purposes. The characterisation orbit is a 9 AM / 9 PM sun synchronous orbit at controlled altitude (2-3 km).
- Orbit transfer: after the characterisation phase, the onboard navigation relative to the asteroid is deployed based on the visual landmark table. When the navigation filter has converged after having taken multiple measurements of the asteroid and its landmarks the ground segment will then command a specific target on the asteroid to be either imaged at high resolution of to be considered as a potential sampling site. The spacecraft will initiate a progressive descent toward the targeted position in order to position itself above the desired target and keep a stationary position relative to it.
- Descent and Sampling: multiple images of the target will be taken and sent to the ground segment for acknowledgement. Depending on the ground segment decision, the spacecraft will either descent toward the sampling site or ascent back on a safe orbit waiting for new instructions. Autonomous onboard GNC is used during that phase.
- Ascent: after sampling completion, the spacecraft will ascend back to a safe orbit altitude while avoiding potential collision with the asteroid.

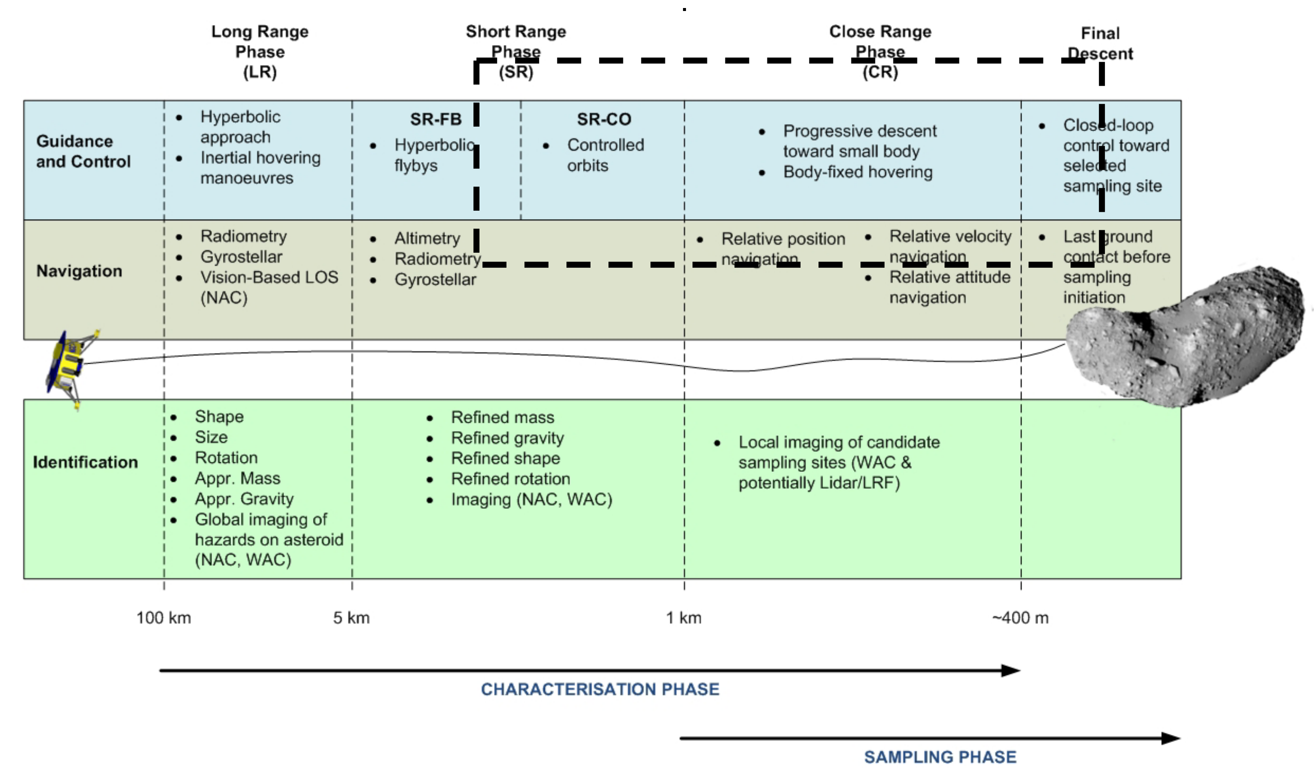


Figure 7.1-1: Characterization and Sampling Phases

7.2 Navigation Chain Design

7.2.1 Vision-based Navigation

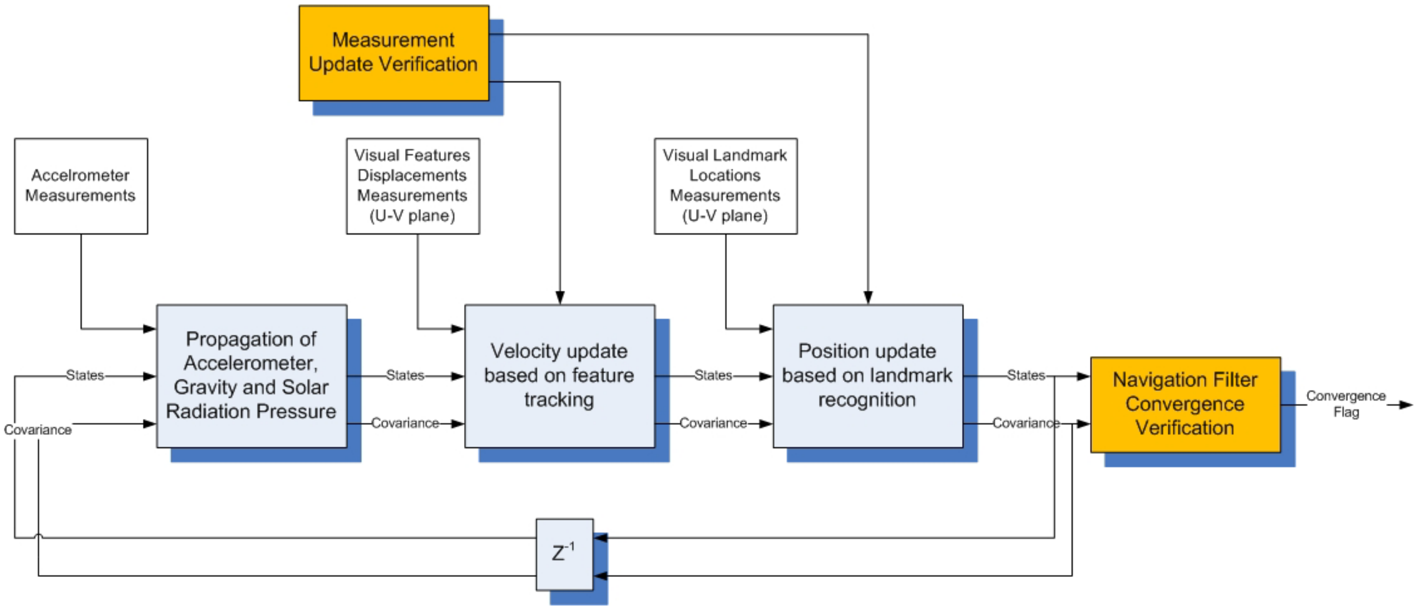


Figure 7.2-1: Block Diagram of Translational State Estimator

For the descent phase a vision-based navigation approach is foreseen. It is based on the tracking and the recognition of surface features on the asteroid surface using a Wide Angle Camera. Local features are tracked in successive images in order to estimate motion between consecutive images while landmarks extracted in images taken by the camera are recognised in a landmark database in order to estimate the actual position of the spacecraft in the asteroid frame. The estimation is based on the Extended Kalman Filter (EKF) theory. The translational state estimation block diagram is shown in the figure above.

7.2.2 Surface Mean Plane Estimator

In addition to the vision-based navigation filter, a specific surface mean plane estimator is used in the last meters of the descent to ensure a perfect alignment of the spacecraft with the ground. The proposed approach is to rely on a specific GNC sensor composed of 4 fixed laser beams. This sensor allows estimating the average range to the surface mean plane and also its relative orientation with respect to the spacecraft.

8. EARTH RE-ENTRY CAPSULE (ERC)

8.1 ERC Main Components and Dimension

The ERC main components and dimensions are depicted in following figures, while the following chapter describe the ERC main subsystems.

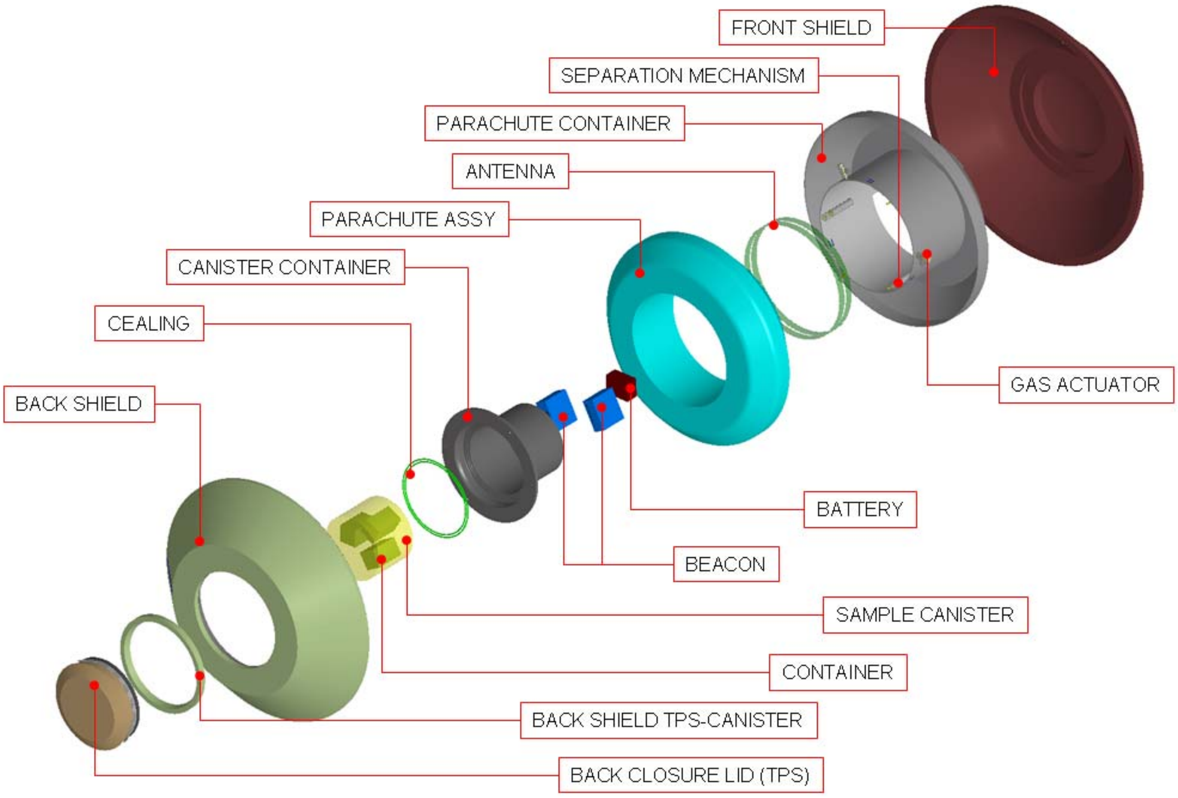


Figure 8.1-1 ERC Exploded View – Main Components

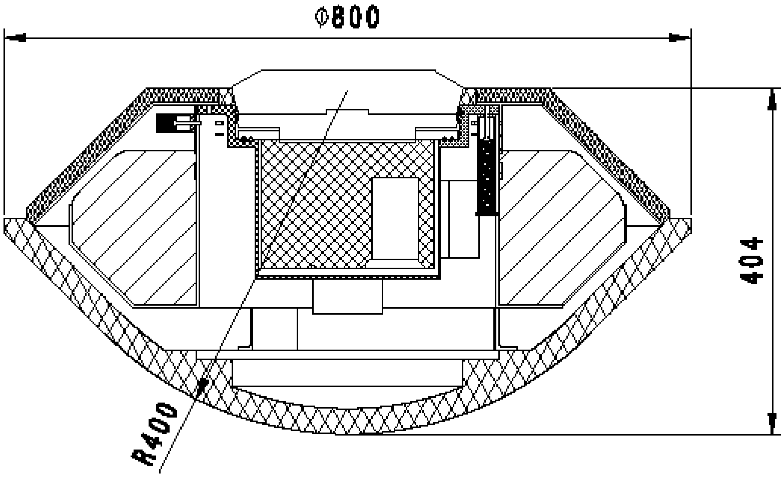


Figure 8.1-2 ERC Main Dimensions

8.2 ERC SubSystems

The Mechanical Support Structure is composed of two main parts:

- An internal cylinder to support and accommodate the Back Closure Lid and the Sample Container, made of CFRP (Intermediate Module), and Aluminum for Closure Lid Interface
- An External structure providing the parachute accommodation and the mechanical interfaces with the Front Shield and the spring actuated parachute deploy mechanism. This part also provides accommodation of the wraparound antenna and is made of CFRP (Intermediate Module)

The Back Closure Lid is composed of two parts:

- A Thermal Protection Shield (TPS) part made of Norcoat Liege.
- A mechanical and locking part made of aluminum which also includes the metallic O-ring sealing.

The proposed Parachute Deploy Mechanism is composed by two main parts (working principles depicted in Figure 8.2-1):

- A gas generator actuated part, mated to the Back Shield, providing the mechanical locking and release function
- A spring actuated lower part, mated to the structure, providing the Back Shield expulsion function

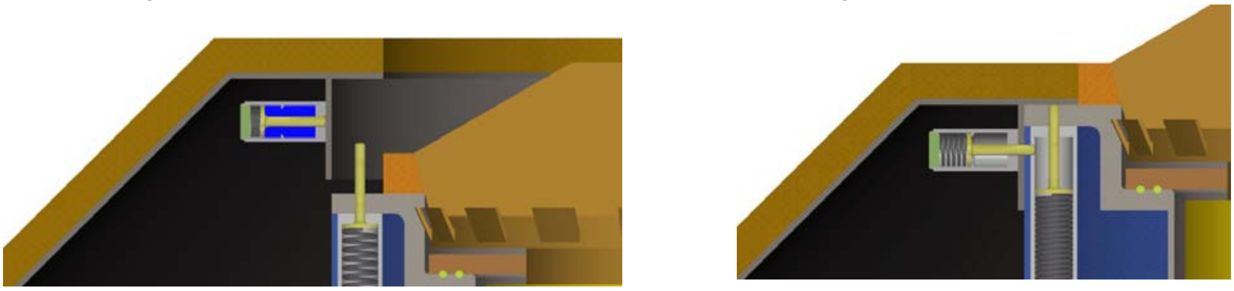


Figure 8.2-1 Parachute Deploy Mechanism Locked (Left) and released (Right) Configuration

The reference Sample Canister to be accommodated inside the ERC has a nominal dimension of 200 mm diameter and 150 mm height, the internal layout will allow the accommodation of 3 Squared Sample Containers.

The ERC shall implement RF beacon capability for Search and Rescue for 5 days after landing. As no space standard is applicable, the proposed design is based on the existing Search & Rescue infrastructure (ARGOS, COSPAS) working at UHF frequency (around 400MHz) for military/civil purposes. Beacon transmission starts after parachute deploys and lasts 5 days after capsule's landing. They are powered by Li-Thyonil cells.

Front Shield Proposed Design/Technology:
- Material: Carbon-Phenolic (Aleastrasil as alternative, but heavier and lower performance)
- Thickness 30 – 33.5 mm
- Insulation: 20 mm RVC, 40 deg @ inner surface

Back Shield Proposed Design/Technology:
- Material: Norcoat Liege supported by CFRP structure
- Total thickness 17 mm

9. SPACECRAFT SUBSYSTEM AND BUDGETS

9.1 Guidance Navigation & Control (GNC)

The AOCS hardware includes the following units:
- 2 LN200 Inertial Measurement Units
- One self-redundant 3-head Hydra Star Tracker, providing high performance inertial pointing.
- 4 Teldix Reaction Wheels of 12 Nms capacity, operated with 3+1 redundancy.
- 2 Wide Angle Cameras
- A self-redunded 4-beam laser range finder
- 2 Coarse Sun Sensors (TNO)

9.2 Telemetry, Tracking and Command (TT&C)

The TT&C subsystem provides telecommunications services for the Marco Polo Orbiter. An X band link (at around 8GHz) is used for standard telecommand, telemetry, ranging according to ECSS standards. The TT&C also supports dedicated communication session to support Radio Science operation and monitoring of the Asteroid Descent and Landing phase as per Beagle 2 recommendations.

The TT&C subsystem of the Marco Polo Orbiter is composed by the following items:
- *One 1.3m diameter High Gain Antenna* (HGA, VEX heritage) with 2-DOF pointing mechanism, used to perform RSE and S/C communications in X-Band.
- *One X-band Medium Gain Antenna* (MGA) with a 2-DOF pointing mechanism, used as backup of HGA e.g. during safe mode or in case of HGA missed pointing.
- *Two omnidirectional X-Band Low Gain Antennas* (LGAs) used during LEOP and/or when spacecraft attitude is not known (e.g. in case of loss of attitude).
- *Two X/X Band Transponders* (XPND) operated in hot redundancy for the receiving part and cold redundancy for the transmitting one.
- *Two 65W X-Band Travelling Wave Tube Amplifiers* (TWTA) that provide the necessary RF amplification to the signal coming from the Transponder (MEX heritage).

9.3 Electrical Power Subsystem (EPS)

The baseline design adopted for the Power System Architecture is a 28 V Maximum Power Point Tracking (MPPT) fully regulated bus. It is based on GaAs triple junction solar cells and Li-Ion battery cell. The solar array area is about 8 m^2, the solar array mass is about 30 kg and the battery mass is about 24 kg.

9.4 Data Handling Subsystem (DHS)

Marco polo DHS architecture will be based on a centralised configuration (GOCE-like) based on a Central Data Management Unit (CDMU) acting as the primary processing and I/O unit for the AOCS, propulsion and communications systems. The CDMU will act as the central communication node between the S/C and the Ground Station distributing or executing commands received from ground, collecting, formatting and transmitting the satellite and instrument telemetry. High computing power is required by both Data Handling and AOCS. The proposed CDMU is an up-to-date version (based on LEON 2FT processor) of a design with long heritage (i.e. GOCE CDMU), which will be adapted to the needs of Marco Polo.

9.5 Propulsion Subsystem

The propulsion architecture is based on a common bi-propellant system. All equipments, with the only exception of the pressurant and propellant tanks, can be found on the European market. It shall be noted that the propellant and oxidiser volume required of around 300 litres sits in the gap of existing European propellant tanks: a delta development of existing tanks may be pursued to optimise volume usage and reduce mass. Due to configuration constrains a 6 tanks configuration based on the ATK 80387-1 has been selected. According to GNC inputs and mission analysis requirements the following hardware is selected for the propulsion system:

- 8+8 4 N Thrusters Model S4
- 2+2 22 N Thrusters Model S22

The 4 N thrusters are necessary for attitude control, asteroid orbital and descent operations while the 22 N are used for the deep space manoeuvres.

9.6 Thermal Control Subsystem

The thermal design is based on a passive thermal control with the use of standard equipments such as Black Kapton and Aluminized Kapton MLI, Optical Solar Reflector (OSR), Loop Heat pipe (LHP), doublers, heaters and thermistors. The S/C configuration allows arranging the radiative area on the lateral panel. Because in some operational conditions the radiative area directly faces the solar flux, OSRs or silver Teflon tape have been considered as finishing surface to reduce the absorb solar flux. The external surfaces are covered by black Kapton MLI except the external payloads covered by MLI with external surface in silver Teflon. The inside of the spacecraft is black painted for temperature homogenization except batteries and propulsion system that are covered with MLI. During the descent phase the IR flux will decrease the efficiency of the radiator located on the lateral panel. For items with high power dissipation the lateral location of radiator is not enough to control the temperature. A possible solution is to locate the radiator on the top of S/C, where the direct IR flux, from the asteroid, is not present.

9.7 Budgets

The total mass budget (main spacecraft and Earth re-entry capsule) is 1558 kg including 20% system margin plus propellant and adapter, compliant with the requirement at launch (Soyuz-Fregat performance up to 1629 kg). The mass of the Earth Re-entry capsule alone is approximately 69 kg.

The power budget amounts to about 560 W in local characterisation mode, compatible with the end-of-life performance of the about 8 m² solar array.

10. DEVELOPMENT, AIV AND PROGRAMMATICS

The Marco Polo development will follow the usual rules for ESA's science program. After the Phase 0/A, the overall Marco Polo project consists the following phases:

- Phase A/B1: definition phase, where the main design aspects will be identified and frozen
- Phase B2/C/D: implementation phase, where the detailed design will be consolidated, the Satellite will be developed and qualified
- Phase E: launch campaign, technical support for Satellite on-orbit commissioning

For the above phases the following durations and main reviews are planned:

Phase	Duration	Milestones and events
Phase B1/B2	24 months	KO, BDR, PDR
Phase C/D	63 months	CDR, TRR, FAR
Phase E1	3 months	LRR

Since the primary structure is not a recurrent item but is a resizing of Hershel-Plank one, the proposed model philosophy is a Proto Flight approach at system level, based on three models:

- One Structural/Thermal Model (STM) for structure and thermal qualification. The STM will be composed by dummies/STM of the equipments. It will include also the ERC STM.

- One Avionics Test Bench (ATB) for SW and functional qualification. It will be composed of EM units or representative BB with real On Board SW.

- One Protoflight Model (PFM) – this is the model to be launched – for acceptance test campaign, satellite functional verification, flight acceptance and pre-launch certification.

2 years of technological study are foreseen to reach the request TRL.for the following items:

- GNC during the proximity phase
- ERC
- T&G Legs
- SATS

For what concern the GNC performances, the proximity phase shall be deeply verified in the SW development phase and later on using the test benches at system level (ATB).

END OF DOCUMENT